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SCATTERING OF 42-MeV ALPHA PARTICLES FROM ^{65}Cu

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SCATTERING OF 42-MeV ALPHA PARTICLES FROM ^{65}Cu

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Recent shell model calculation[1] for ^{63}Cu and ^{65}Cu have shown that an extended particle-core coupling scheme with configuration mixing is a good approximation to the more exact shell model calculations. The simple weak-coupling model can not explain the low-lying states in many odd A nuclei. For ^{63}Cu, the number of states predicted by the weak coupling model and the relative strengths are in poor agreement with the inelastic scattering data.[2,3] Also several of the states are found to have large single particle strengths in stripping reactions.[4] Thankappan and True's extended particle-core calculation[5] explained the properties of the low-lying levels of ^{63}Cu.

^{63}Cu has been studied by inelastic alpha particle scattering,[6] and the alpha scattering of Bruge[2] et al suggest ^{65}Cu is similar. Similar results for ^{63}Cu and ^{65}Cu were obtained for inelastic proton scattering.[3] However, for those states resulting from the coupling of a particle with the octupole core state, the lack of structure in the inelastic angular distributions did not permit reliable angular momentum transfer assignments. Since inelastic alpha scattering angular distributions are more characteristic of the angular momentum transfer, and known to excite collective states, 42-MeV alpha particles were scattered from ^{65}Cu with better resolution than early work.[2] The extended particle-core coupling model[5] has been used to predict the properties of the low lying levels of ^{65}Cu.

The experiment was done using the 42-MeV alpha particle beam of the NASA Lewis 160 cm cyclotron. The scattering system, shown in figure 1, included magnetic analysis of the incident beam and particle detection by lithium-drifted silicon semiconductors. The energy resolution of the experiment was 80-100 kev and angular distributions were measured for 10 to 50 degrees in the center of mass system. A typical energy spectrum is shown in figure 2. The accuracy of the angle setting was ±0.05 degrees and the zero direction was determined by right-left scattering. A four detector mount allowed simultaneous measurement of cross sections at four different angles. Data taken forward of 20 degrees had a detector separation of 2^{o} and the angular resolution was $\pm 0.06^{o}$. Beyond 20^{o} the angular separation was increased to 4^{o} and a resulting angular resolution of $\pm 0.12^{o}$. The target was an isotopically enriched foil of 0.996 ^{65}Cu with an area density of $0.694^{mg}/cm^{2}$.

The data was reduced by fitting the peaks with a skewed Gaussian function using a least-squares computer program(7) with a linear background search. The energy calibration of each system was done by pulser and the excitation energies are accurate to ±25 kev. The relative cross sections are known to an accuracy of ±3% and the absolute cross sections to ±10%.

The elastic angular distribution is shown in figure 3 along with the optical model fit. The six parameter optical model calculation was done using the computer program SCATLE.(8) The resulting optical model parameters are listed on figure 3.

The inelastic angular distributions of the states with angular momentum transfer of $l = 2$ are shown in figure 4. The weak coupling model predicts four states with their excitation strengths proportional to $(2J_f + 1)$ and their energy centroid equal to that of the ^{64}Ni 2^{+}core state. Experimentally, there are three strongly excited states and three weaker states all having similar angular distributions. Ths solid lines in the figure are the distorted wave calculations done using DWUCK.(9)

The inelastic angular distributions of the states observed with an angular momentum transfer of $l = 3$ are shown in figure 5. Again one would expect 4 excited states. Four strongly excited states are observed and three weaker states all having an $l = 3$ angular distribution.

The simple particle-core model predicts that the excited states should have the same reduced transition probability to the ground state as the 2^+ core state in the even core nucleus. In table I are listed all the states that were excited strong enough in this experiment to obtain angular distributions. The Δl are assigned on the basis of the DWBA fits to the angular distributions. The relative strengths are measured by β'_l, the partial deformation parameter, where,

$$\beta'_l(J_f) = \beta_l \sqrt{\frac{2J_f + 1}{(2l + 1)(2J_i + 1)}} \tag{1}$$

and are shown in the third column. The spins and parity assignments shown in the fourth column are taken from previous works.[10] The deformation parameters, β_l, shown in the fifth column are calculated using equation (1) and the assigned spins. The sixth column shows the ratio of the reduced transition probability for the states in ^{65}Cu to that of the core excited state in ^{64}Ni. Of the predicted quartet of states corresponding to the coupling of the $p_{3/2}$ proton to the 2^+ core state, only three are seen. The excited state having the same spin as the ground state, $3/2^-$, is not present. The $3/2^-$ state at 1.706 MeV is too weak to fit the simple model although it gives an excellent centroid prediction. Perey[11] assumed that the strength of the $3/2^-$ state would be weakened due to mixing with the ground state. The simple core-particle model has it's greatest success if the ground state spin is not included in the excited multiplet.[12]

Little can be said about the octupole-coupled states because the spins are not known. Again there are more than the four excited states predicted. The state at 2.53 MeV is the strongest excited state as was

the case for inelastic proton scattering.[3] Blair[4] reports a strong $l = 4$ transition to a state at 2.54 MeV. If this is the same state there must be considerable configuration mixing and the simple particle-core model will not give accurate results. In the last two columns of table I the ratios of the reduced transition probabilities are compared for inelastic protons[3] to the present experiment. Since the errors in the ratios are large not much can be said about these ratios.

On the bases of the evidence that the collective and single particle states are mixed, the calculation of Thankappan and True[5] was extended to ^{65}Cu to describe the low-lying levels. The Hamiltonian of the system was taken to be of the form:

$$H = H_c + H_p + H_{INT} \tag{2}$$

where H_c is the Hamiltonian describing the ^{64}Ni core, H_p is the Hamiltonian describing the single $p_{3/2}$ proton moving in the average potential of the core and H_{INT} is the core to particle interaction. The form of H_{INT} was taken as:

$$H_{INT} = -\xi\left(\tilde{J}_c^{(1)} \cdot \tilde{j}_p^{(1)}\right) - \eta\left(\tilde{Q}_c^{(2)} \cdot \tilde{Q}_p^{(2)}\right) \tag{3}$$

where $\tilde{J}_c$ and $\tilde{j}_p$ are, respectively, the total angular momentum operators for the core and particle. $\tilde{Q}_c$ and $\tilde{Q}_p$ are, respectively, the mass quadrupole-moment operators of the core and particle and ξ and η are strength parameters.

Since the model does not specify the exact nature of the core states, it is not possible to calculate the reduced matrix elements for $\langle J_c' \| \tilde{Q}_c^{(2)} \| J_c \rangle$, so these quanities are treated as parameters. For the calculation two core states and three single particle states were considered. The core states were the 0^+ ground state and the first 2+ state at 1.348 MeV in ^{64}Ni. The three single particle states used were the $p_{1/2}$, $p_{3/2}$ and $f_{5/2}$ orbitals. The energy spacing between the $p_{3/2}$ and $p_{1/2}$ orbitals and $p_{3/2}$ and $f_{5/2}$ orbitals were taken

from the ^{63}Cu calculation[5] and adjusted slightly for better agreement to the data. With the single particle energies fixed, the three adjustable parameters of the model are:

(1) ξ, the depole-dipole interaction strength
(2) $\chi_1 \equiv \eta \langle 0 \| \tilde{Q}_c^{(2)} \| 2 \rangle$
(3) $\chi_2 \equiv \eta \langle 2 \| \tilde{Q}_c^{(2)} \| 2 \rangle$

Since the states in ^{65}Cu have the same reduced transition probability as the 2^+ core state in ^{64}Ni, it is possible to calculate,

$$\langle 0 \| lc\tilde{Q}_c^{(2)} \| 2 \rangle = \left[5B(E2)\downarrow \text{ of } {}^{64}\text{Ni} \right]^{1/2} \tag{4}$$

using the positive square root.

Figure 6 shows the resulting energy levels obtained from the calculation compared to the experimental results. The parameters were the same as those used in the ^{63}Cu calculation[5] except the $p_{1/2} - p_{3/2}$ energy was reduced to 1.20 MeV. The values of the parameters used are listed on figure 6. The calculated low-lying energy levels agree well with the data.

In table II the calculated ratios of $B(E2)\downarrow$ are compared to the experimental data. Since no octupole-octupole terms were included in H_{INT}, E3 reduced transition probabilities could not be calculated. The large errors in the experimental values makes it difficult to compare the ratios.

In table III the components of the wave functions for the calculated energy levels are listed. The square of the amplitudes of the $|0, j_p\rangle$ parts of the eigenfunctions will give the percentage of the single particle admixtures in a level. In the last column of table III are shown the specroscopic strengths measured by Blair.[4] The calculated results agree with the experiment quite well and the extent of the configuration mixing is evident. If the total strength of the 2^+ core state is mixed into all six of the $l = 2$ angular distributions experimentally observed, then the total deformation parameter,

$$\beta_2 = \sqrt{\Sigma(\beta_2')^2} \tag{5}$$

should equal the core strength of $\beta_2 = 0.20 \pm 0.015$. However, the total $l = 2$ strength is experimentally measured to be $\beta_2 = 0.160 \pm 0.014$. Also, if we assume the octupole strength to be spread out over the seven $l = 3$ angular distributions, we get $\beta_3 = 0.145 \pm 0.011$ as compared to a core $\beta_3 = 0.181 \pm 0.016$. So considering all the $l = 2$ and $l = 3$ strength experimentally measured in ^{65}Cu, the total core strength is not found.

The simple weak coupling model can not account for the experimentally observed quantities of the low lying levels of ^{65}Cu. The extended particle-core calculation has shown that the coupling is not weak and considerable configuration mixing of the low lying states results.

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TABLE I

LEVEL, MeV	Δl	β'_l	J^π	β_L	R_{alpha}	R_{PROTON}[a]
0.771	2	0.0578	$1/2^-$	0.183±0.016	0.836±0.226	1.00±0.17
1.114	2	.0977	$5/2^-$	.178±0.014	.795±0.208	1.21±0.22
1.482	2	.108	$7/2^-$	.172±0.014	.730±0.202	.95±0.18
1.629	2	.0234	$(5/2)^-$	.042±0.004	.045±0.012	.20±0.05
1.706	2	.0222	$3/2^-$	.049±0.003	.060±0.015	---------
2.098	2	.0365	$(5/2)^-$	.066±0.005	.105±0.021	---------
2.344	--	------	-----	-----------	-----------	---------
2.530	3	.0864	$(9/2)^+$	.122±0.011	.455±0.136	1.25±0.20
2.858	--	------	-----	-----------	-----------	---------
3.044	3	.0666	-----	-----------	-----------	---------
3.310	3	.0683	$(5/2)^+$	.124±0.011	.467±0.014	1.30±0.30
3.494	3	.0624	-----	-----------	-----------	---------
3.709	3	.0335	-----	-----------	-----------	---------
3.930	3	.0331	-----	-----------	-----------	---------
4.047	3	.0496	-----	-----------	-----------	---------
4.180	--	------	-----	-----------	-----------	---------

$R = B(E2)\downarrow {}^{65}Cu / B(E2)\downarrow {}^{64}Ni$

THE ERROR IN THE ENERGY LEVELS IS ±25 keV.

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[a]A. L. MCCARTHY & G. M. CRAWLEY.

TABLE II

LEVEL, MeV	J^π	β_2	R	β_2	R	R CALC
		ALPHA SCATTERING		PROTON SCATTERING		
0.771	$1/2^-$	0.183±0.016	0.836±0.226	0.200±0.010	1.00±0.17	1.003
1.114	$5/2^-$	.178±0.014	.795±0.208	.220±0.014	1.21±0.22	.786
1.482	$7/2^-$	.172±0.014	.730±0.202	.195±0.014	.95±0.18	.928
1.629	$(5/2)^-$	.042±0.0038	.045±0.012	.078±0.007	.20±0.05	.440
1.706	$3/2^-$	.049±0.0032	.060±0.015	-----------	---------	-----
2.098	$(5/2)^-$	.066±0.005	.105±0.021	-----------	---------	.42

$R = B(E2)\downarrow {}^{65}Cu / B(E2)\downarrow {}^{64}Ni$

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TABLE III

EIGENFUNCTIONS

ENERGY, MeV	J^π	$\lvert 0, p_{1/2}\rangle$	$\lvert 0, p_{3/2}\rangle$	$\lvert 0, f_{5/2}\rangle$	$\lvert 2, p_{1/2}\rangle$	$\lvert 2, p_{3/2}\rangle$	$\lvert 2, f_{5/2}\rangle$	C^2S CALC	C^2S BLAIR[1]
0	$3/2^-$	------	0.9286	------	0.1810	-0.3070	0.1034	0.86	0.79 $p_{3/2}$
.776	$1/2^-$	0.8809	------	------	------	-.4116	-.2334	.79	.75 $p_{1/2}$
1.143	$5/2^-$	------	------	0.7224	-.1044	-.6422	-.2343	.52	.26 $f_{5/2}$
1.451	$7/2^-$	------	------	------	------	.9869	.1612	----	.054
1.565	$5/2^-$	------	------	.5234	-.4243	.7194	-.1686	.27	.57 $f_{5/2}$
2.133	$3/2^-$	------	.1612	------	.5821	.7855	-.1345	----	.073 $f_{5/2}$

[1]A. G. BLAIR ${}^{64}Ni({}^{3}He, d){}^{65}Cu$.

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EXPERIMENTAL ARRANGEMENT

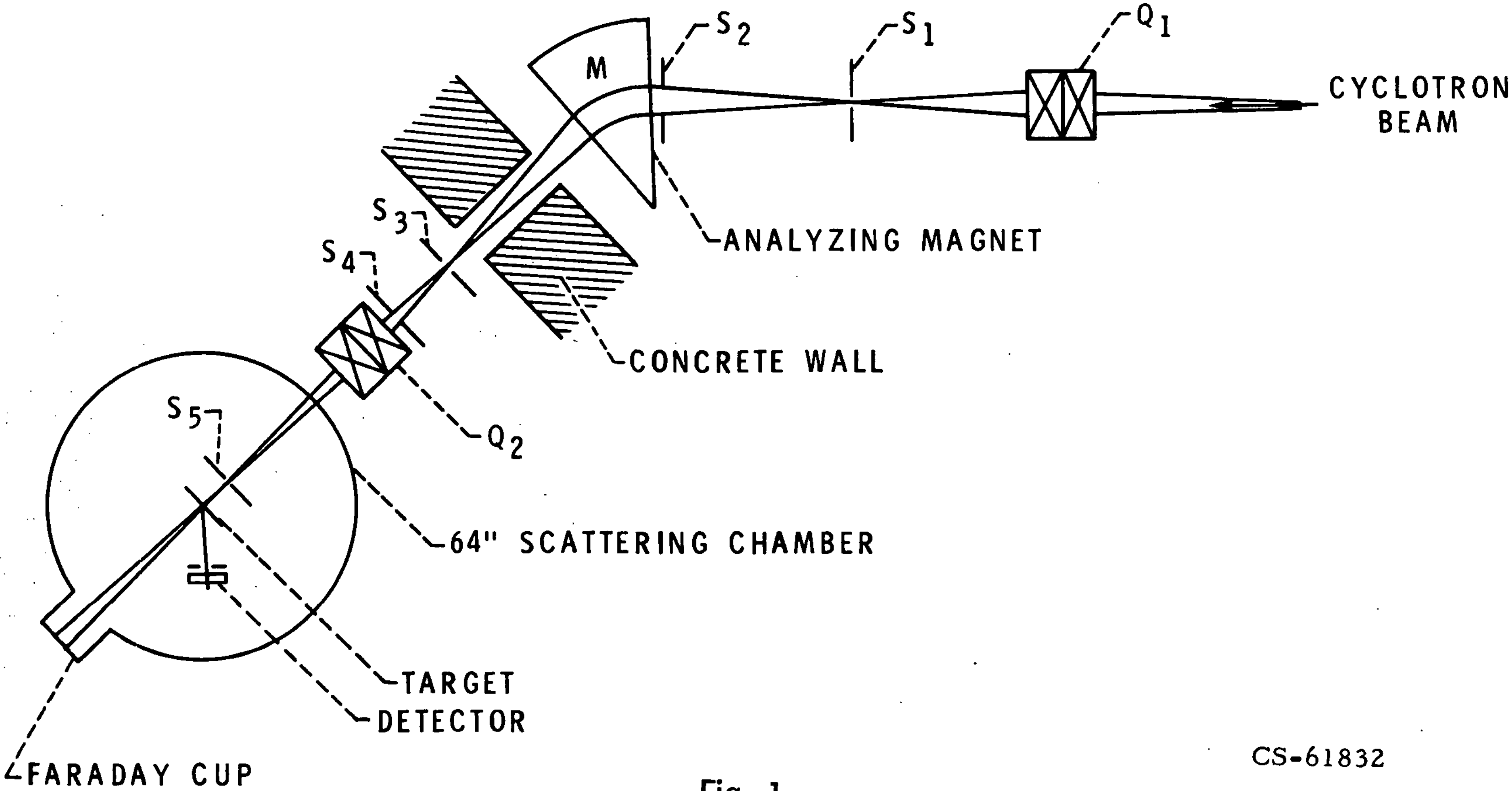

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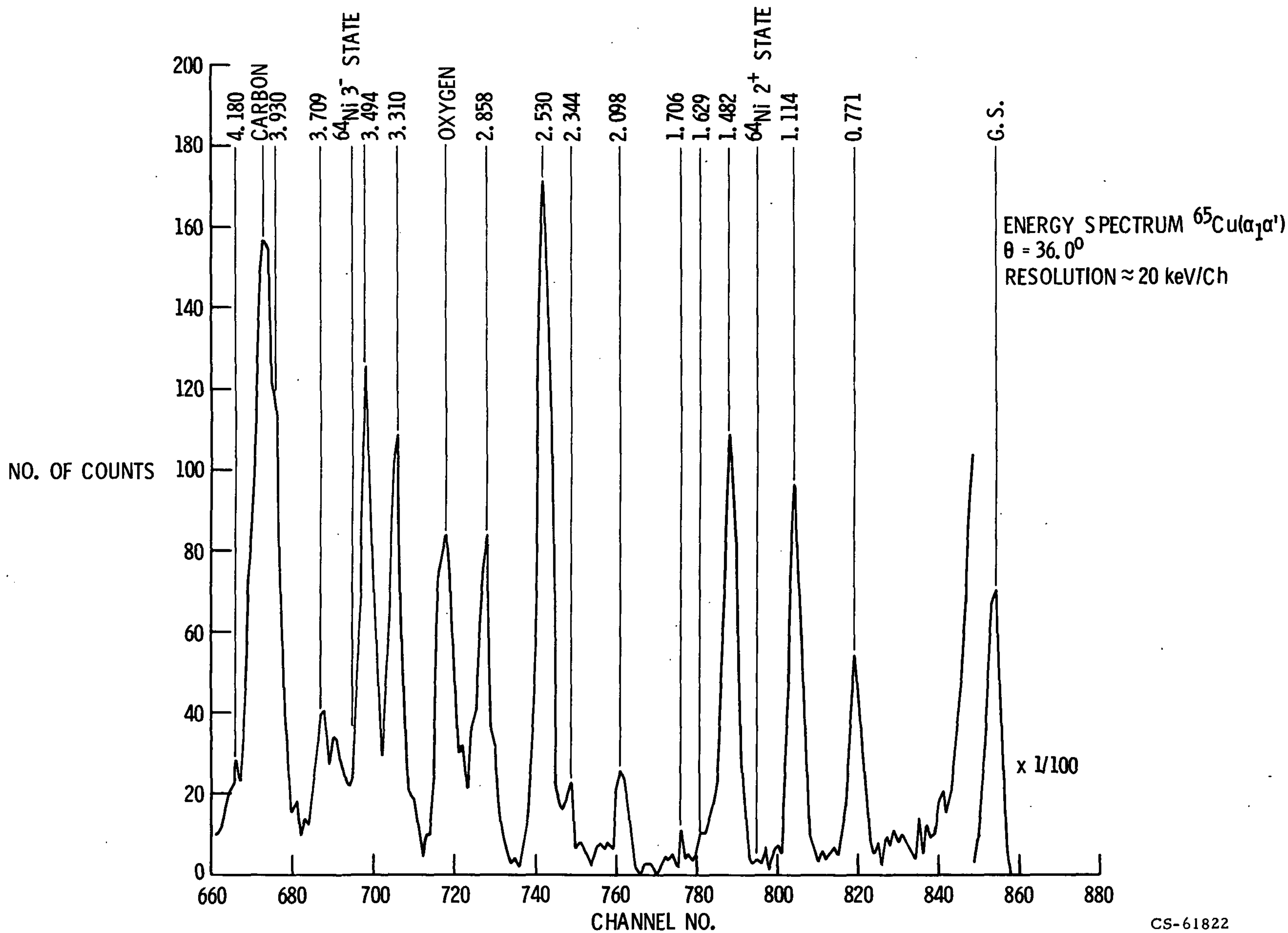
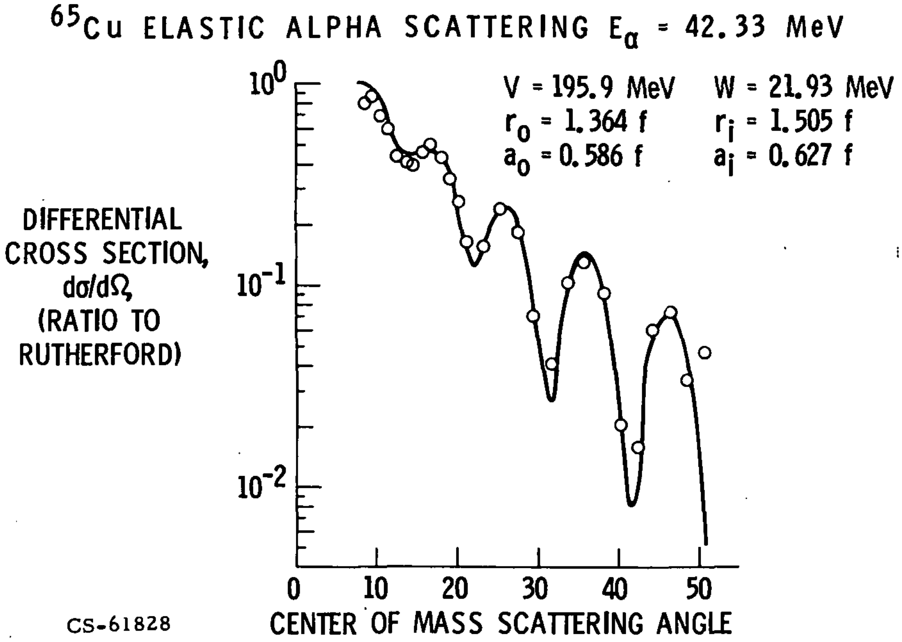
Fig. 1



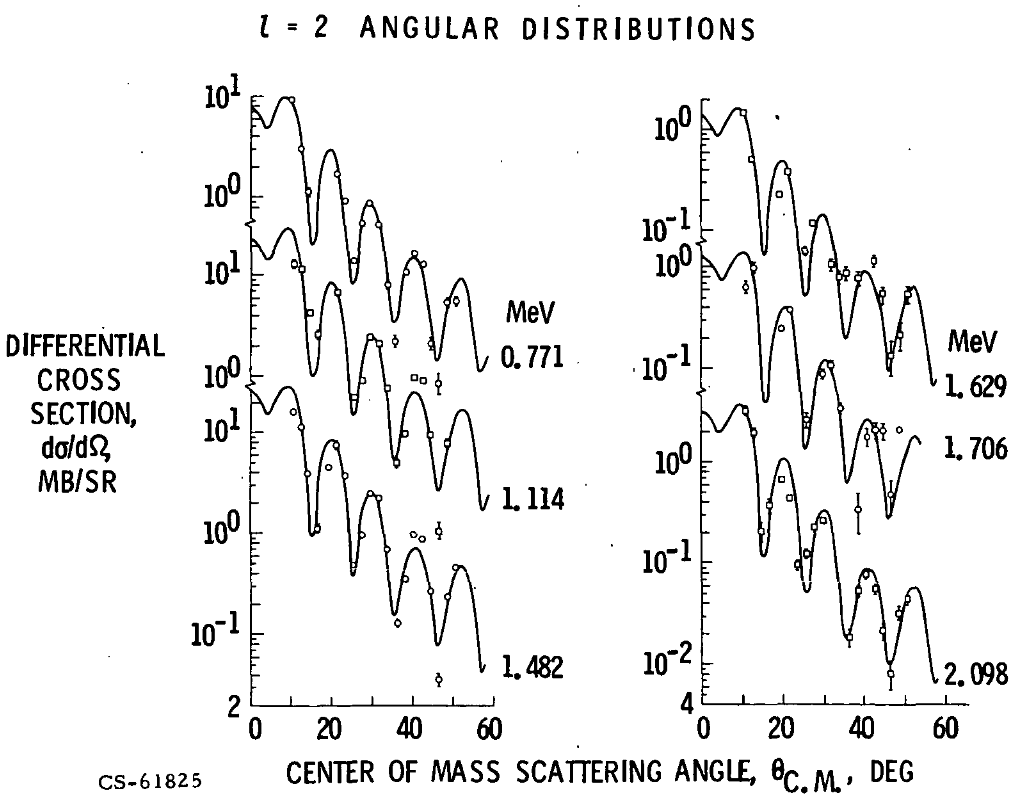
4.180
CARBON
3.930
3.709
64Ni 3- STATE
3.494
3.310
OXYGEN
2.858
2.530
2.344
2.098
1.706
1.629
1.482
64Ni 2+ STATE
1.114
0.771
G.S.
ENERGY SPECTRUM 65Cu(α1α')
θ = 36.0°
RESOLUTION ≈ 20 keV/Ch
x 1/100
NO. OF COUNTS
CHANNEL NO.
CS-61822

Fig. 2



^{65}Cu ELASTIC ALPHA SCATTERING E_α = 42.33 MeV
V = 195.9 MeV
W = 21.93 MeV
r_0 = 1.364 f
r_i = 1.505 f
a_0 = 0.586 f
a_i = 0.627 f
DIFFERENTIAL CROSS SECTION, $d\sigma/d\Omega$, (RATIO TO RUTHERFORD)
10^0
10^{-1}
10^{-2}
0
10
20
30
40
50
CENTER OF MASS SCATTERING ANGLE
CS-61828

Fig. 3



l = 2 ANGULAR DISTRIBUTIONS
DIFFERENTIAL CROSS SECTION, $d\sigma/d\Omega$, MB/SR
MeV
0.771
1.114
1.482
MeV
1.629
1.706
2.098
10^1
10^0
10^{-1}
10^{-2}
2
4
0
20
40
60
CENTER OF MASS SCATTERING ANGLE, $\theta_{C.M.}$, DEG
CS-61825

Fig. 4

$l = 3$ ANGULAR DISTRIBUTIONS

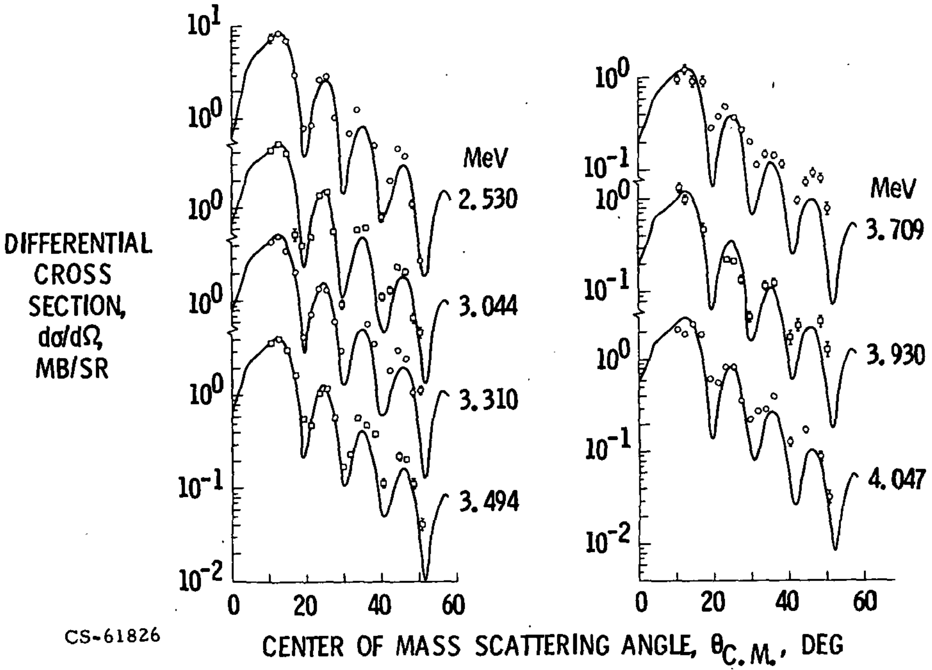


Fig. 5

COMPARISON OF EXPERIMENTAL & CALCULATED ENERGY LEVEL FOR ^{65}Cu

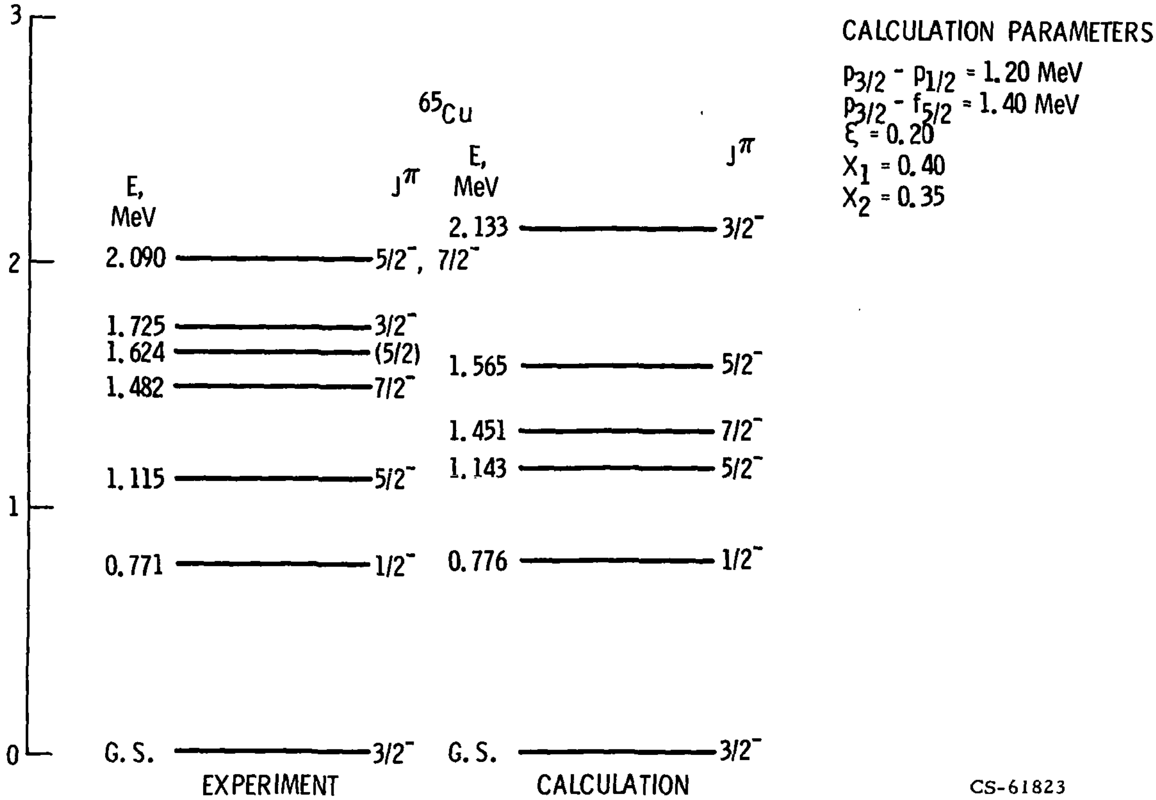


Fig. 6